Supersymmetric standard model with strong electroweak symmetry breaking

Tonnis ter Veldhuis
Macalester College

Based on: arXiv:1107.3116

In collaboration with: Thomas Clark (Purdue University)
Sherwin Love (Purdue University)

19th International Conference on Supersymmetry and Unification of Fundamental Interactions, August 28 till September 2, 2011, Fermilab, Batavia, Illinois USA.

Introduction

- We consider the possiblity that some novel strong gauge field dynamics may be the source of the electroweak symmetry breakdown.

- A nonlinear realization of the $SU(2)_L \times U(1)$ symmetry breakdown provides a model independent means of characterizing this dynamics.

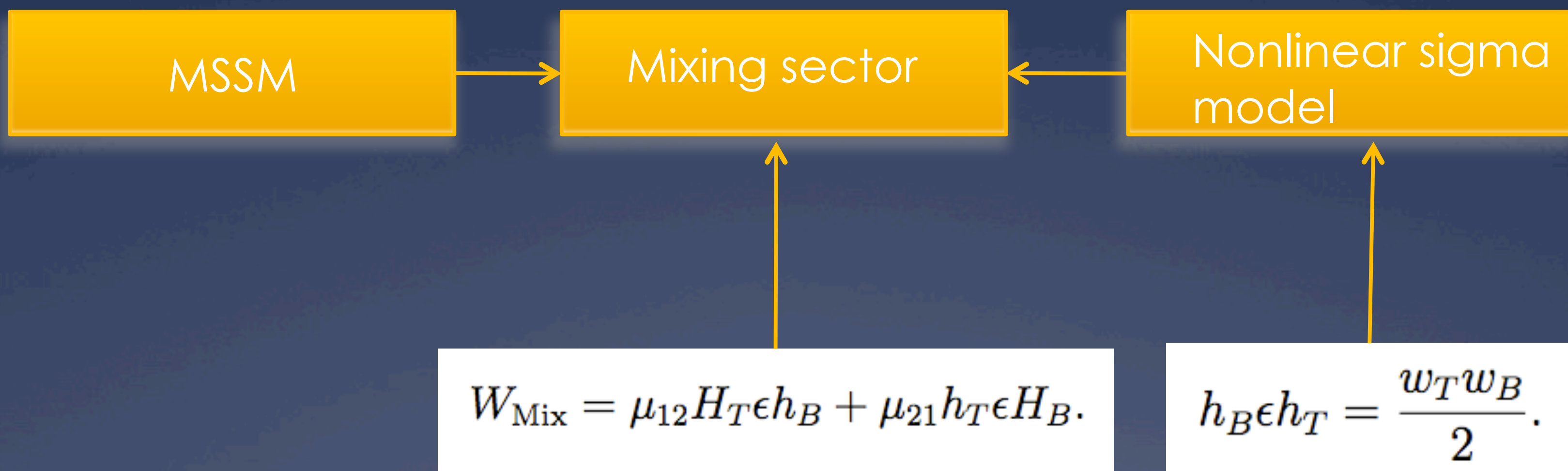
- In our supersymmetric model, electroweak symmetry is nonlinearly realized through an additional pair of constrained Higgs doublet superfields.

- The superpotential coupling of the regular MSSM Higgs doublet pair to the constrained doublets catalyzes their vacuum expectation values.

- Leptons and quarks receive their masses only from the regular MSSM Higgs doublet pair sources.

- The W and Z boson masses are given by the vacuum expectation value of both the constrained and regular types of Higgs doublets.

The MSSM plus strong EW breaking sector



$$W_{\mathrm{Mix}} = \mu_{12} H_T \epsilon h_B + \mu_{21} h_T \epsilon H_B .$$

$$h_B \epsilon h_T = \frac{w_T w_B}{2} .$$

- The MSSM sector includes the usual pair of Higgs doublets and mu parameter.
- A second pair of Higgs doublets satisfies a chiral superfield constraint.
- Soft Susy breaking is limited to the MSSM sector.

The constrained doublets have the form:

$$h_T = \begin{pmatrix} h_T^+ \\ h_T^0 \end{pmatrix} = \begin{pmatrix} i\pi^+ \\ \sigma - i\pi^0 \end{pmatrix} \quad , \quad h_B = \begin{pmatrix} h_B^0 \\ h_B^- \end{pmatrix} = \begin{pmatrix} \sigma + i\pi^0 \\ i\pi^- \end{pmatrix}$$

These sigma-model coordinates are given by the chiral superfields $\pi^{\pm} \equiv \pi^1 \mp i\pi^2$ and $\pi^0 = \pi^3$, while the superfield constraint implies:

$$\sigma = \sqrt{\frac{w_T w_B}{2} - \vec{\pi} \cdot \vec{\pi}}$$

The vacuum expectation values of these constrained doublets are:

$$< 0|h_T|0 >= \begin{pmatrix} 0 \\ w_T/\sqrt{2} \end{pmatrix} \quad , \quad < 0|h_B|0 >= \begin{pmatrix} w_B/\sqrt{2} \\ 0 \end{pmatrix} .$$

Parameter space

○ For simplicity, the nonlinear realization of the electroweak symmetry has been taken to exhibit the custodial $SU(2)_V$ global symmetry, hence the corresponding vacuum values are chosen to satisfy $w_T = w_B = w$.

○ As a consequence the Higgs/gauge sector mass spectrum depends on 7 parameters:

M_1 and M_2
$\tan\beta = v_T/v_B$
μ
b

← Usual MSSM parameters

$\tan\theta = \sqrt{(v_T^2 + v_B^2)/2w^2}$
μ_{12}

← Additional parameters

○ The SUSY breaking terms m_{HT}^2 and m_{HB}^2, and the mixing mass μ_{21} are fixed by the 3 electroweak breaking minimum conditions.

Mass spectrum

- The spectrum contains one additional scalar, one additional pseudo-scalar, two additional charged scalars, one additional neutralino, and two additional charginos compared to the MSSM. (In essence the components of one neutral and two charged chiral superfields)

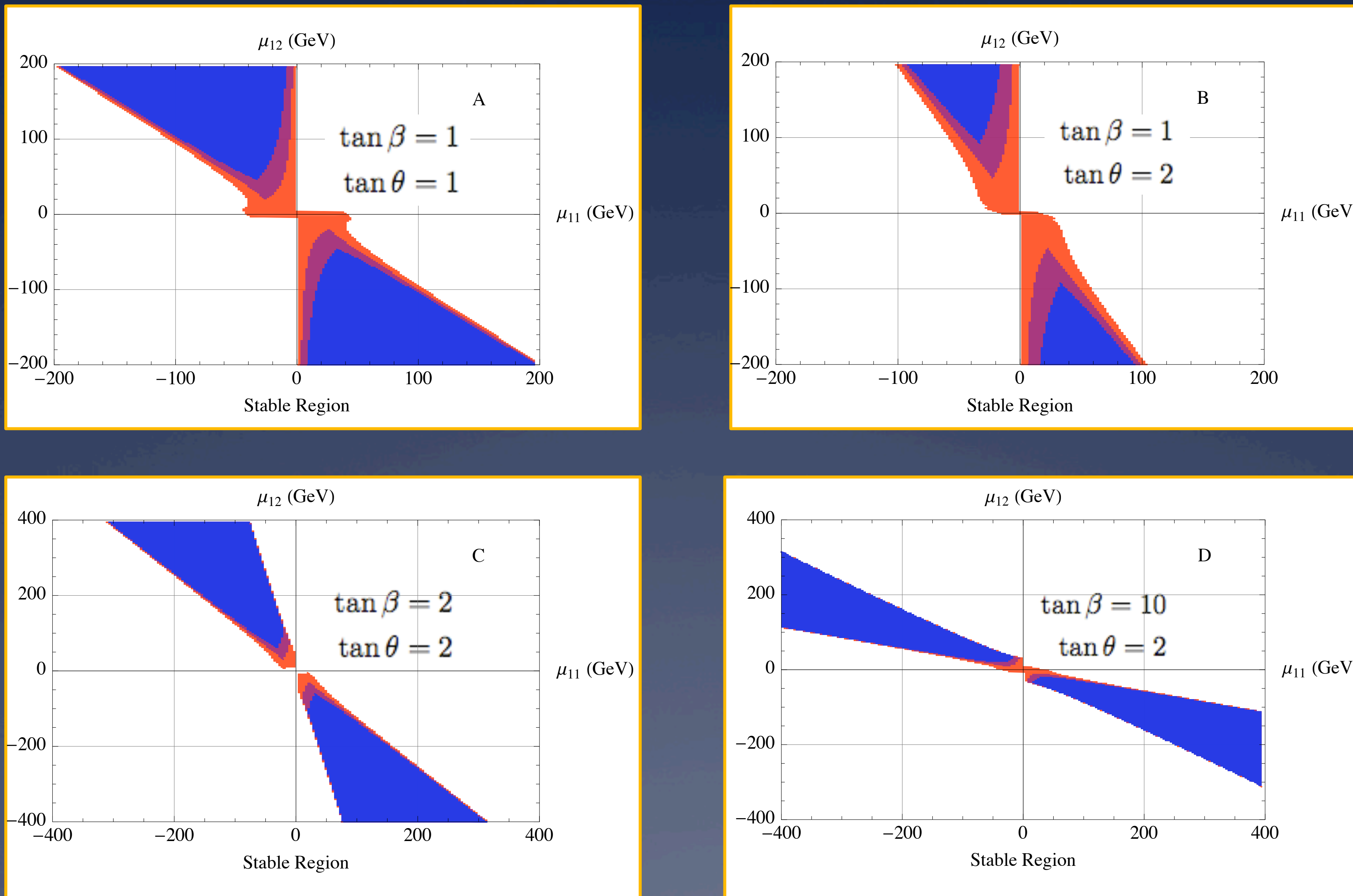
- The scalar potential is obtained while taking into account the non-trivial Kahler metric.

- Requiring the extremum of the potential to be a minimum in all directions restricts the viable parameter space.

- In contrast with the MSSM, the mass of the lightest scalar is not bound to be below M_Z at tree level.

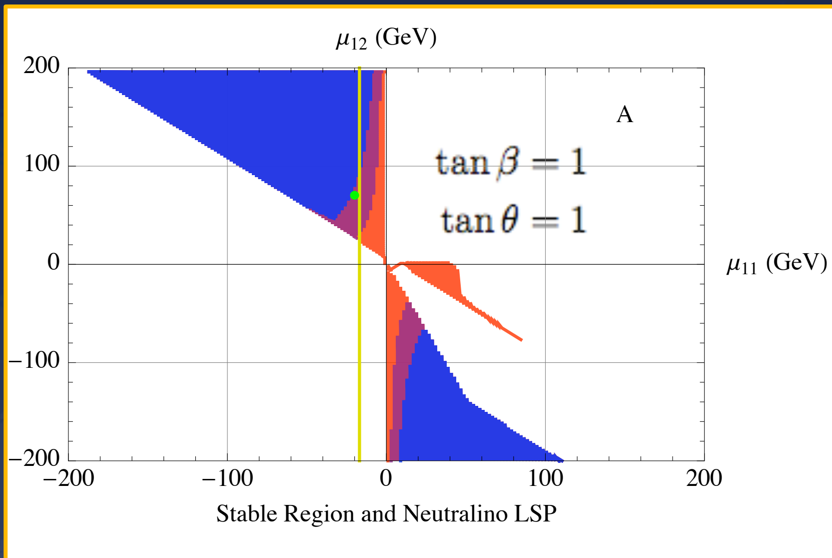
- An unbroken R-parity dictates the stability of the lightest supersymmetric particle (LSP). Requiring it to be a neutralino further limits parameter space.

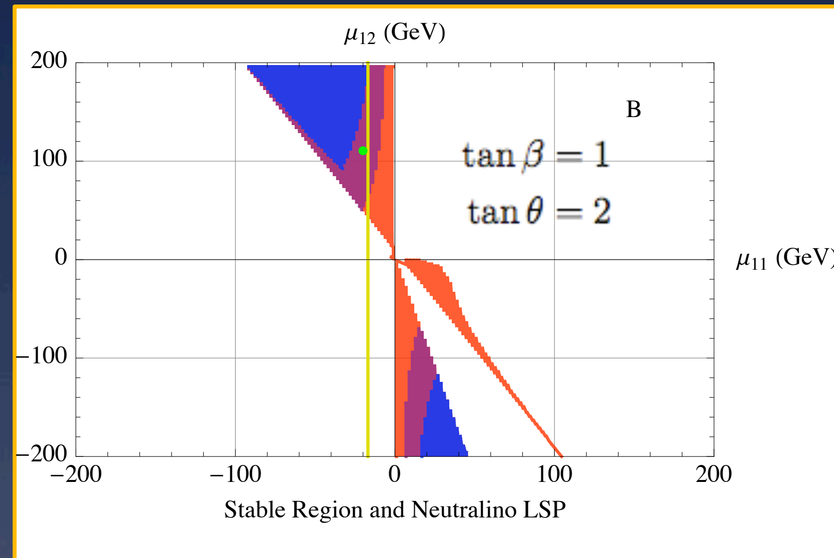
Parameter space constraints

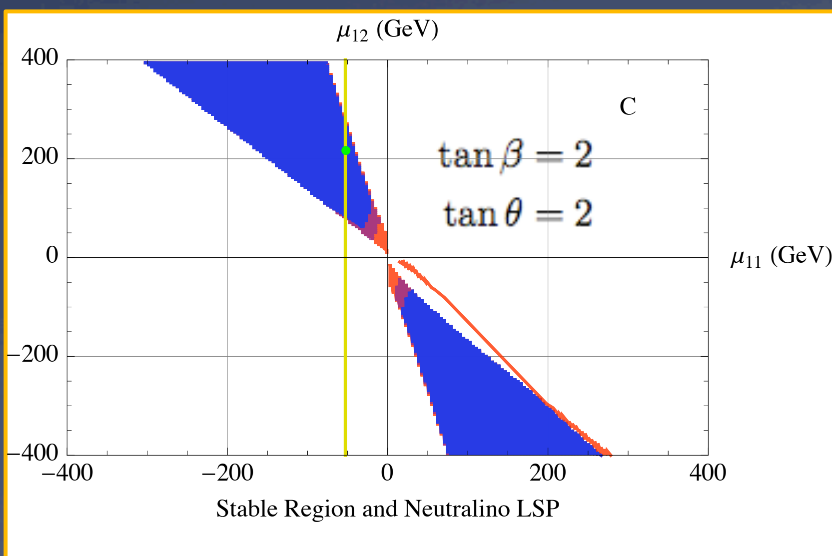


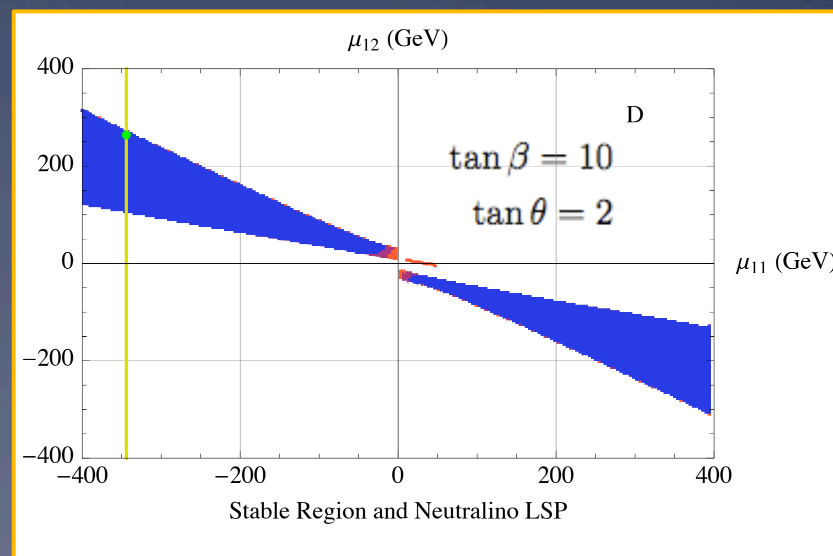
$b = -4,000\ \mathrm{GeV}^2$ $b = 4,000\ \mathrm{GeV}^2$ $b = 12,000\ \mathrm{GeV}^2$

Parameter space constraints



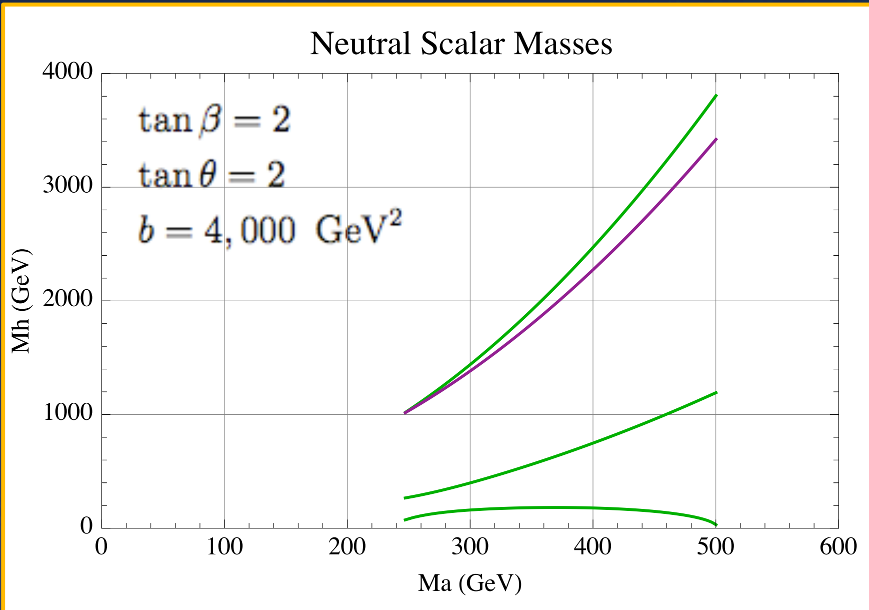


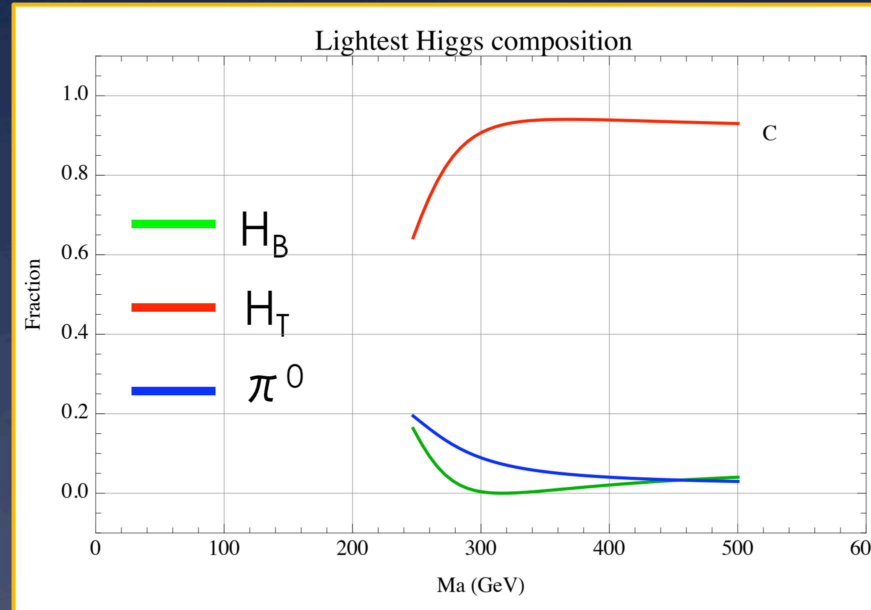


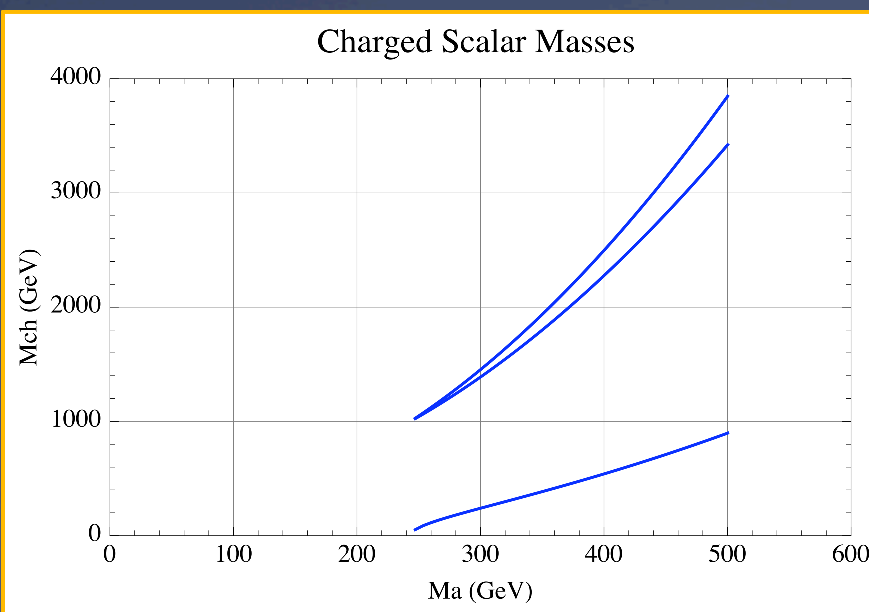


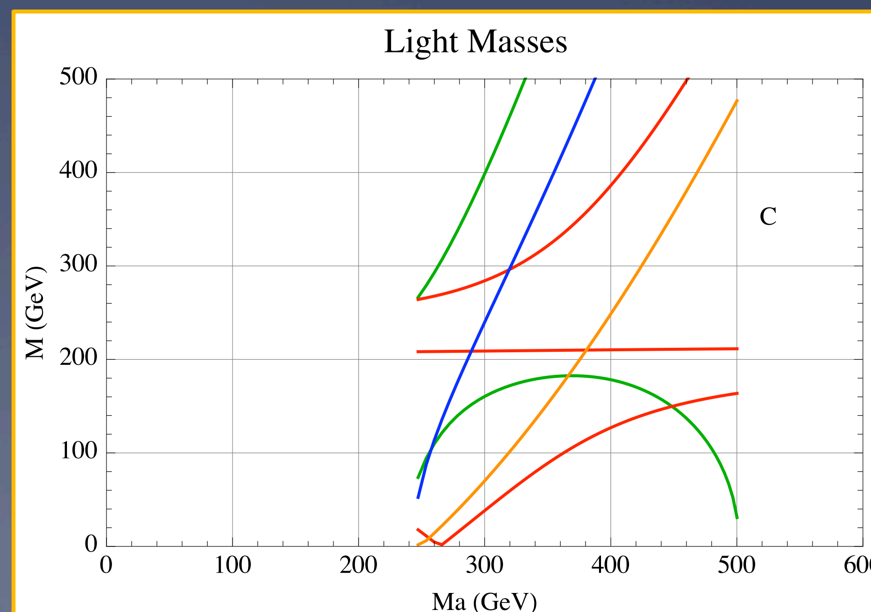
$b = -4,000\ \mathrm{GeV}^2$ $b = 4,000\ \mathrm{GeV}^2$ $b = 12,000\ \mathrm{GeV}^2$

Scalar mass spectrum

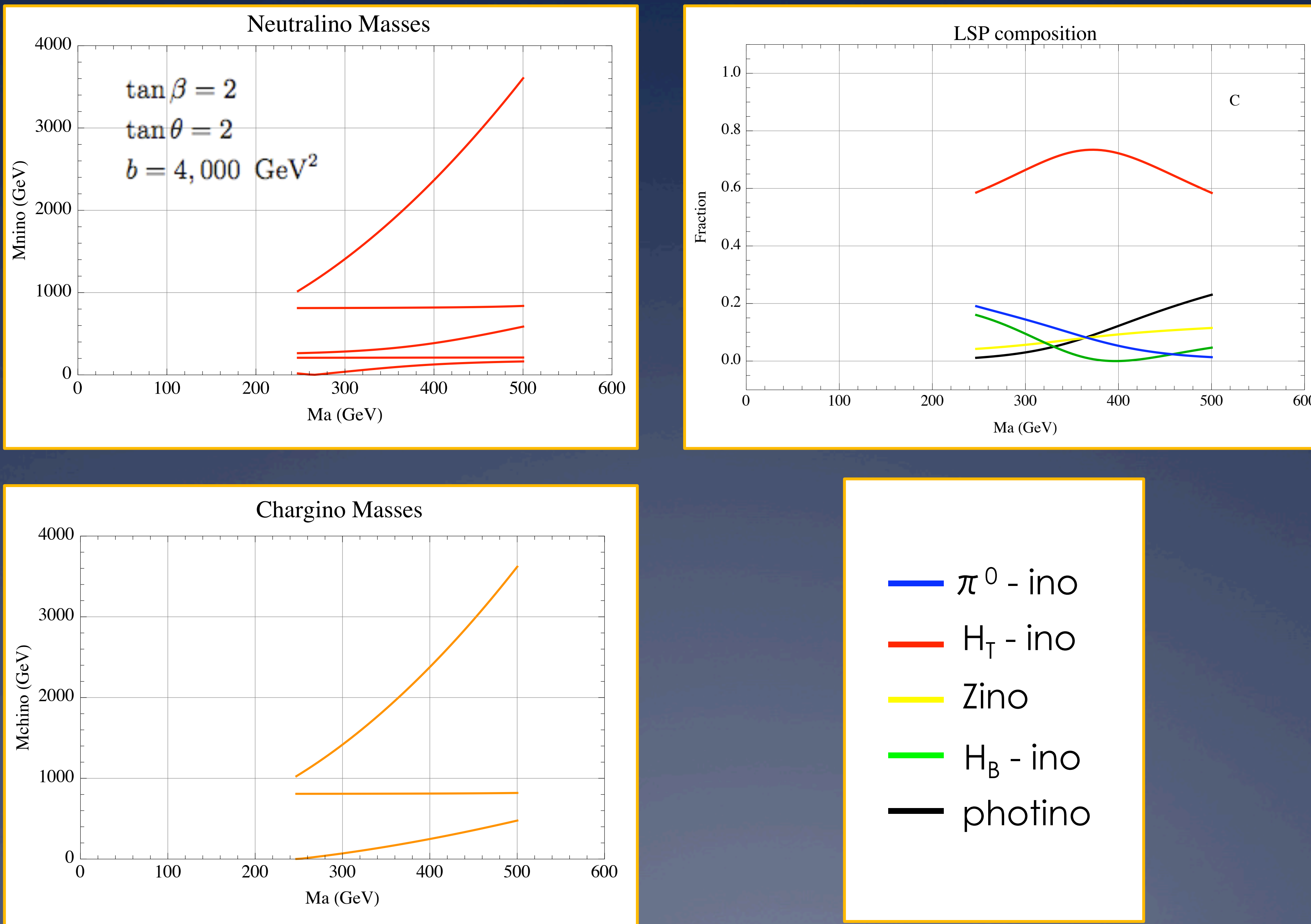








Fermion masses



Perturbative Yukawa couplings

The W and Z masses are given in terms of all the vacuum expectation values. Since the MSSM Higgs field vacuum expectation values only partially contribute to the electroweak vacuum value v = 246 GeV, the matter field Yukawa couplings must be larger in order to compensate for the smaller v_T and v_B values.

Placing a perturbative bound on the size of the Yukawa coupling constants so that $y < 4\pi$ results in bounds on $\tan\beta$ and $\tan\theta$:

$$
\begin{aligned}
\left[1+\frac{1}{\tan^2\theta}\right]\left[1+\frac{1}{\tan^2\beta}\right] &= \frac{y_t^2 v^2}{2m_t^2} \leq \frac{8\pi^2 v^2}{m_t^2} \approx 165 \\
\left[1+\frac{1}{\tan^2\theta}\right]\left[1+\tan^2\beta\right] &= \frac{y_b^2 v^2}{2m_b^2} \leq \frac{8\pi^2 v^2}{m_b^2} \approx 2.2\times 10^5 \\
\left[1+\frac{1}{\tan^2\theta}\right]\left[1+\tan^2\beta\right] &= \frac{y_\tau^2 v^2}{2m_\tau^2} \leq \frac{8\pi^2 v^2}{m_\tau^2} \approx 1.5\times 10^6 .
\end{aligned}
$$

Thus small fractional values of $\tan\theta$ and $\tan\beta$ are excluded (e.g. $\tan\theta = 0.1$ and $\tan\beta = 1$) as well as excessively large values of $\tan\beta$.

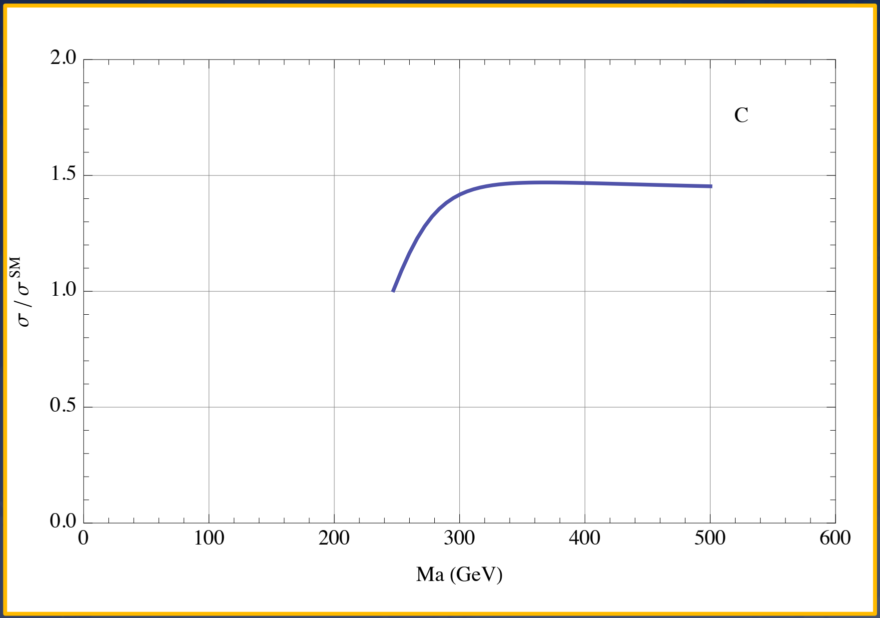
Higgs production

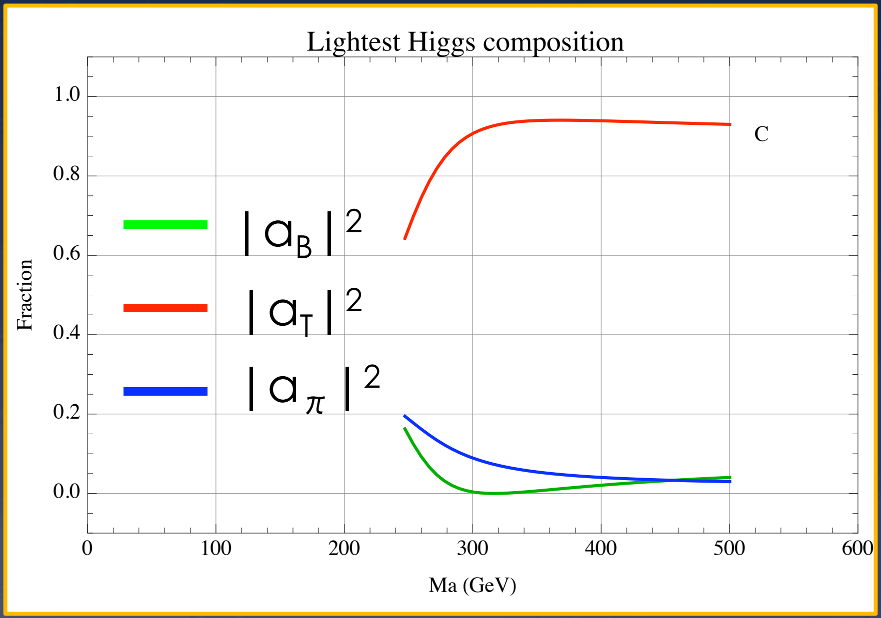
For moderate tan β, the top quark loop contribution is dominant for gluon fusion Higgs production. The lightest Higgs boson is a linear combination of the H_T^0, H_B^0 and π^0 fields:

$$h = a_T S_T + a_B S_B + a_\pi S_\pi$$

The top quark only interacts with the S_T component with the enhanced Yukawa coupling mt /(v sin θ sin β). The production rate is thus equal to that of the standard model times the overall factor

$$\sigma = a_T^2 \left(1 + \frac{1}{\tan^2\theta}\right)\left(1 + \frac{1}{\tan^2\beta}\right)\sigma^{\rm SM}$$





Higgs production cross-section is enhanced due to enhanced top Yukawa coupling, and suppressed due to the mixing of the Higgs fields.

Higgs decay

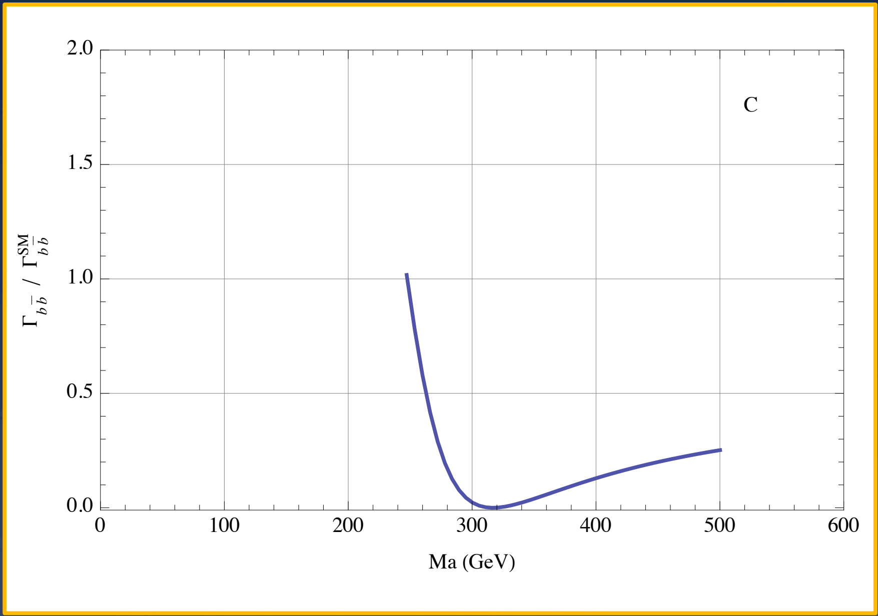
Although the coupling to the electroweak gauge fields is universal, the vacuum values come into play for the decay process as well as the composition of the light Higgs particle.

Since the scalar field coupling to the W^+W^- is just through the H_T^0 and H_B^0 fields as the π^0 was taken to respect the custodial $SU(2)_V$ symmetry, the tree level decay rate to W^+W^- is the standard model rate modified by a suppression factor:

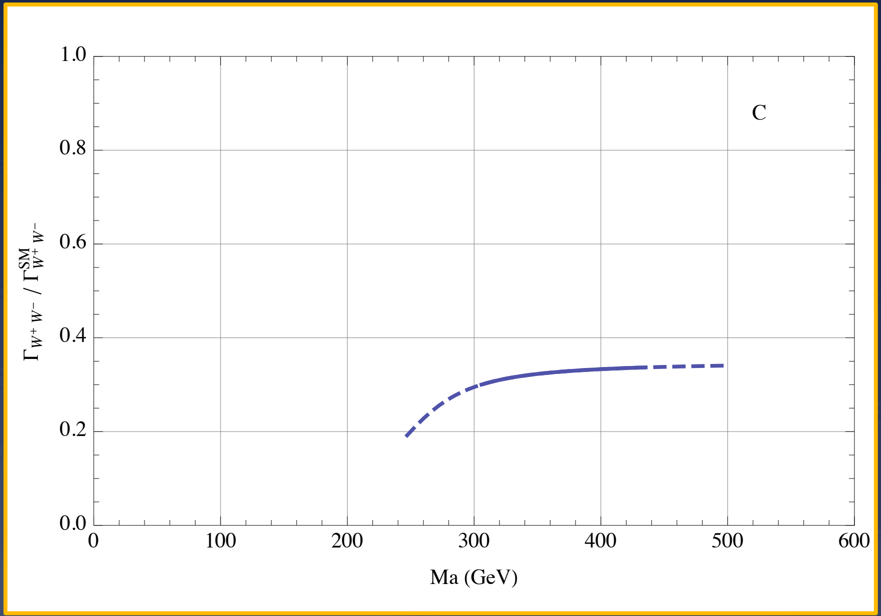
$$\Gamma_{W^+W^-} = \left(\frac{\tan^2\theta}{1+\tan^2\theta}\right)\left(\frac{1}{1+\tan^2\beta}\right)\left[a_T \tan\beta + a_B\ \right]^2 \Gamma^{SM}_{W^+W^-}$$

Likewise the decay to b-quarks depends on the b-Yukawa enhancement and the constituent suppression of the HB content of the physical Higgs field. This leads to the modified tree level rate

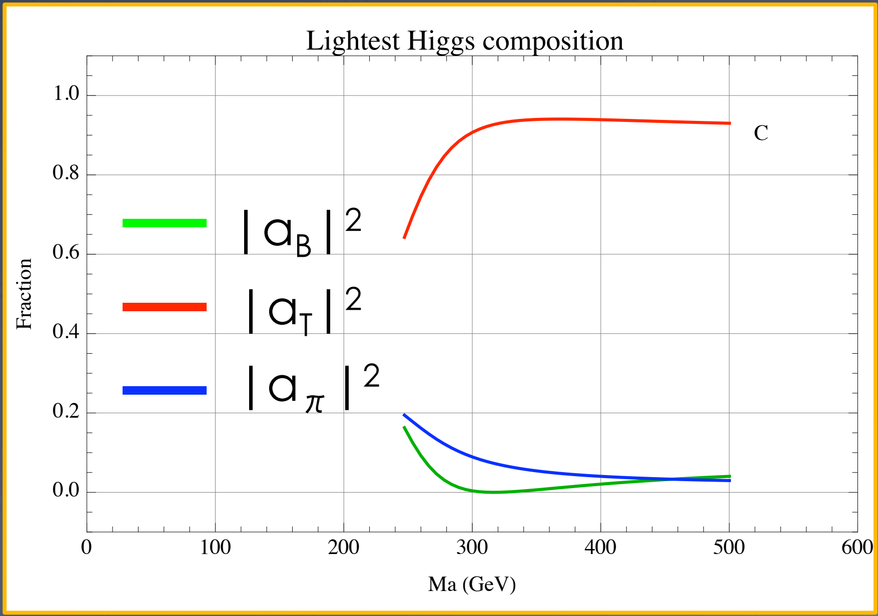
$$\Gamma_{b\bar{b}} = a_B^2\left(1+\frac{1}{\tan^2\theta}\right)\left(1+\tan^2\beta\right)\Gamma^{SM}_{b\bar{b}}$$



$\Gamma_{b\bar{b}} \,/\, \Gamma^{SM}_{b\bar{b}}$
C
Ma (GeV)



$\Gamma_{W^+W^-} \,/\, \Gamma^{SM}_{W^+W^-}$
C
Ma (GeV)



Lightest Higgs composition
Fraction
$|a_B|^2$
$|a_T|^2$
$|a_\pi|^2$
C
Ma (GeV)

Precision Measurements

The effects of radiative corrections to the gauge field vacuum polarizations are encapsulated in the electroweak precision parameters S and T. There are many supersymmetric higher dimensional operators, albeit surpressed by powers of the effective action cutoff, denoted $\Lambda \geq 4\pi v$, that contribute to S and T. For example:

$$\begin{aligned}\Gamma_{S22} &= \frac{-s_{22}}{128 g_1 g_2 \Lambda^2}\left(\int dS h_T \epsilon W_2 W_1 h_B + \int d\bar{S}\bar{h}_T \epsilon \bar{W}_2 \bar{W}_1 \bar{H}_b\right) \\ &= \frac{s_{22} w^2}{8\Lambda^2}\int d^4x \left[\sin 2\theta_W \left(Z_{\mu\nu}Z^{\mu\nu} - A_{\mu\nu}A^{\mu\nu}\right) - 2\cos 2\theta_W Z_{\mu\nu}A_{\mu\nu} + \cdots\right],\end{aligned}$$

The contribution of this and similar operators to S is given by:

$$\alpha S / \sin 2\theta_W = \frac{\left(s_{11} v_T v_B + s_{12} v_T w + s_{21} v_B w + s_{22} w^2\right)}{\Lambda^2},$$

while they do not contribute to T . Likewise their are several effective operators that contibute directly to T but not to S .

Summary

- We considered a modified version of the MSSM coupled to a strongly interacting EW symmetry breaking sector.

- The model has a viable mass spectrum. The lightest Higgs boson mass is not bound from above by M_Z at tree level.

- Pertubative bounds on the Yukawa couplings for the top and bottom quarks and τ lepton provide a further restriction on the parameter space.

- Higgs production and decay are modified due to the extra vacuum expectation values and Higgs field mixing.

- Additional constraints imposed due to the electroweak precision tests.